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Biodiesel production from *Xanthoceras sorbifolia* in China: Opportunities and challenges

Zeng-Yu Yao [a,*], Jian-Hua Qi [a], Li-Ming Yin [b]

[a] Key Laboratory for Forest Resources Conservation and Use in the Southwest Mountains of China, Ministry of Education, Southwest Forestry University, Kunming 650224, China
[b] Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, China

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ABSTRACT

With a deep concern over the energy shortage and climate change, biodiesel has become more attractive to governments globally. *Xanthoceras sorbifolia* Bunge, an endemic oilseed tree to China, has been identified as a major woody energy plant for biodiesel production and receives special support from Chinese governments for its development. This paper analyzes the opportunities and challenges for biodiesel production from *X. sorbifolia* in China. The biological characteristics, geographic distribution, site requirements, propagation, cultivation and productivity of this species are described. The information about the presence of various phytochemicals in different parts of the plant is summarized. As a multifunctional tree, it plays other important roles in addition to the oil production for biodiesel, having many potential uses such as soil and water conservation, land reclamation, carbon sink, landscaping, and productions of foods, fodders, medicines and industrial chemicals. The potential advantages and disadvantages of the biodiesel production from *X. sorbifolia* are outlined, and the needs for further research are recommended. The low fruit-setting rate and the small percentage of fine breeds result in a low yield, a high development cost, and a low economic efficiency of the biodiesel production, which is the development bottleneck of the biodiesel industry of *X. sorbifolia* presently. Integral valorization of the co-products such as leaves, branches, hulls, testa and kernel meals can make for the cost reduction and industrial production of the biodiesel from *X. sorbifolia*.

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* Corresponding author. Tel./fax: +86 871 638631 45.
E-mail addresses: z-yyao@hotmail.com, zengyuyao@126.com (Z.-Y. Yao).

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1. Introduction

Energy is the lifeblood for modern civilizations in industries, transport, agriculture and other human needs. In recent years, the fossil-fuel resources are being used up rapidly with consequent environmental degradation. It becomes exceedingly urgent to search alternative fuels based on renewable and clean energy. Biomass is the fourth largest energy source in the world after coal, oil and natural gas and is the largest and most important renewable-energy source in use currently [1]. It is one of the prospective candidates and has been paid much attention by academic communities, companies, and governments.

The energy consumption in China has been growing at 5.5% per annum over the last 30 years, and China has overtaken the US as the world's largest energy consumer. China's increasing demand for energy to power the rapid growth of the economy urges her to find new resources. Under these circumstances, biofuels have been developed to some extent in China which present some further opportunities for this country. Over the past decade, China has been positioned as the world's third largest biofuel producer. Based on the National Mid- and Long-term Planning of Renewable Energy Development, China has set the target to increase the annual use of fuel bio-ethanol to 10 million tonnes and biodiesel to 2 million tonnes by 2020 [2]. However, in consideration of food security for the developing country with 22% population and 7% arable land over the world, biofuels do not have to compete with food systems and with the arable land with food crops in China. Therefore, developing forest bio-energy on marginal land was identified as one of the strategic directions because it does not necessarily compete with food systems. The State Forest Administration (SFA) listed the large-scale cultivation of energy forest as a part of the Eleventh Five-Year Forestry Development Plan. Two important documents, the National Energy Forest Development Planning and the Eleventh Five-year Development Program for Biological Diesel Oil Feedstock Forest Base, have been completed, with the initial concept that, by 2020, 13.33 million ha of energy forests will have been cultivated. Together with the existing forest resources, these will meet 6 million tonnes of biodiesel feedstock and 400 million tonnes of wood fuels each year [3]. Nowadays, SFA cooperates with some state-owned companies, such as PetroChina, Sinopec and China National Off-shore Oil Corporation, on the cultivation of forestry bio-energy. The cooperation built up a developing system of “Forest-Oil Integration” and “Forest-Electricity Integration” from the feedstock cultivation to processing to sales for speeding up the progress in forestry bio-energy. Some local woody species with oil-rich seeds were introduced to biodiesel forest plantations and given special support by Chinese governments. *Xanthoceras sorbifolia*, along with *Jatropha curcas*, *Cornus wilsoniana*, *Pistacia chinensis*, has been planted as a demonstration project. SFA planned to plant *X. sorbifolia* for 1.33×10^5 ha in the Eleventh Five-years, and the total planning area of the local governments has far exceeded this amount. Despite the burning enthusiasm in some provinces for widespread cropping, the tree is currently not commercially viable as a biodiesel feedstock without genetic improvement to enhance its seed yields. The purpose of this review is to analyze the opportunities and challenges for biodiesel production from *X. sorbifolia* in China and offer some suggestions to help avoid risks.

2. Biological characteristics

X. sorbifolia Bunge (*syn X. sorbifolium* Bunge), which is known by various names, e.g., yellow horn, shiny leaf yellow horn, golden horn, and Chinese flowering chestnut, is the sole species of this genus, belonging to the family of Sapindaceae. It is a shrub/small tree growing up to 10 m in height, 90 cm in diameter at breast height, and 9 m in crown width. The leaves are deciduous, alternate, imparipinnate with 9–19 leaflets. The leaflets are lanceolate or narrowly elliptic, sessile, 2–6 cm long and 1–1.5 cm broad, with a sharply serrated margin. The inflorescence is generally a 15–25 cm long raceme, bearing 30–50 erect flowers with 2–3 cm in diameter. The flowers are andromonoecious, and the hermaphrodites usually only appear in the apical inflorescence. The corolla comprises five petals whose upper portion is white, but the base streaked with yellow to purplish crimson with age. The fruit is an oval leathery capsule, 5–6 cm in diameter, with loculicidal dehiscence, 3–4 or very rarely 2 or 5 loculi each with 1–8 (typically 4–6) seeds. The seed is black, spherical, 1.5 cm in diameter [4].

3. Geographic distribution and site requirements

X. sorbifolia is a Tertiary relict plant and endemic to northern China. Wild or cultivated trees were widely found in 18 provinces of China, namely, Beijing, Inner Mongolia, Shaanxi, Shanxi, Hebei, Henan, Shandong, Anhui, Liaoning, Ningxia, Gansu, Xinjiang, Sichuan, Tibet, Qinghai, Heilongjiang, Jiangsu and Jilin. The horizontal range is 28°34′–47°20′ E and 73°20′–120°25′ N, which involves in the temperate and the warm temperate zones. The altitudinal span is 300–2000 m (usually 300–1200). The upper and lower limits depend on the longitude, revealing a trend of a gradual increase from east toward west. This is, perhaps, due to China's topography sloping slightly to the east on the whole. The ravines and gullies on the Loess Plateau are its centralized distribution region. The distribution shows that this species exhibits a wide environmental tolerance. It is tolerant of drought, cold, leanness, salinity and alkalinity. Its climatic growing conditions were described by Mou et al. [5] as the following: a mean annual temperature of 3.3–15.6 °C with monthly averages ranging from −19.4 °C to 0.2 °C in January and 13.6 °C to 32.4 in July, an annual total precipitation of 43–696 mm, a frost-free period of 120–233 days, and an annual sunshine time of 1616–3124h. It is unselective in soil requirement, growing well in deserted mountains, steep hillsides, barren gullies, and sandy lands, and good stands were also found on dry, saline, alkaline, stony, and calcareous soils.

4. Propagation

X. sorbifolia can be propagated by either botanical seed or clone. The former is very well possible, and the germination of the seeds pretreated by cold stratification started after 20 days and continued to 40 days with a nursery germination percentage about 89%. Dry seeds can also be directly sown, but the germination processes are delayed. Seed propagation is a principal means for its cultivation in practice, whereas the plants obtained are individually different in character such as productivity. Asexual reproduction produces offspring with conserved parental traits, thus being helpful in rapid multiplication of superior phenotypes/genotypes. The tree can be propagated by cuttings, which is a cheapest and economical method of clonal propagation. Compared with stem cuttings, root cuttings are more suitable for *X. sorbifolia*, giving about 82.9% survival, much higher than those of hardwood (29.8%) and softwood (41.2%) cuttings. A preference was given to take root cuttings (10 cm in length) in winter (mid-October), sock in 250 mg/L auxin (IBA, NAA, or ABT rooting powder) for 30 s, which gave about 92% rooting [6]. It has been successfully propagated by homoplastic graft. The plant originating from grafted seedling whose scion from the bearing elite tree started fruiting earlier and had much higher seed yield than those from seeds. It is an effective approach for germplasm improvement and productivity enhancement to graft scions from an elite tree into crowns of low-yielding trees [4]. The plant is difficult to mass manipulate by tissue culture, and an efficient regeneration system has not been successfully established as yet. A few reports [7–9] have described the regeneration of the tree under in vitro conditions. Plantlets have been obtained via multiple shoots from nodal segments, somatic embryogenesis from zygotic embryos, and organogenesis from leaf discs and from nodal segments. However, these protocols are hardly used in practice due to their low efficiency.

5. Cultivation

X. sorbifolia habituates poorly to shadowy conditions and grows best on adret. Thus, planting is not done on shady slopes. If there is sufficient rainfall or irrigation for the initial growth phase, direct planting of seeds in the field can be employed. Otherwise, it is recommended that plantations practice transplantation of the seedling. Plant spacing for the tree is generally 2 m × 2 m (2500 trees/ha), 2 m × 3 m (1667 trees/ha), 3 m × 3 m (1111 trees/ha), or 3 m × 4 m (833 trees/ha) [10]. Spacing considerations include site conditions and both of yield and income at the early stage. Wider spacing is more appropriate in arid regions to put off canopy closure, which increases water and light competition. This proposal is unfavorable in the increase of yield and income in the early phase. In order to compensate for this deficiency, a scheme of thick initial planting and then intermediate cutting after canopy closure is proposed. Apart from that, the tree can also be intercropped with other crops such as alfalfa, soybean, and potato in its early years, especially if the wider spacing was used. Despite the tolerances to drought and poor nutrition, however, proper irrigation and fertilization have been proven to increase the rate of fruit set, seed yield and the oil content of seed kernels. There are two key phases sensitive to water and fertilizers, which are fruit growth period and just after fruit harvest. The former favors the growth of the fruits, while the latter does recovery and accumulation of nutrition in the tree for the next year. Given this, in arid and semi-arid areas, two times irrigations together with fertilizations were strongly suggested. Fertilizer amount varies with age and growth vigor of the tree as well as soil nutrition, and suggested ratios of $N:P_2O_5:K_2O$ have been 20:5:1 for the former and 20:3:1 for the latter [4]. *X. sorbifolia* produces flowers in inflorescences from newborn branches, and hence the number of new branchlets determines the number of inflorescences. Therefore, pruning is essential to increase the number of fruiting branchlets in the tree. Pruning in first three or four years is important to lessen flowering and fruiting and to build ideal crown architecture. However, very limited studies try to precisely and scientifically demonstrate the influence of pruning on the seed yield of the tree.

6. Insects, diseases and their management

Mono-cropping could result in the spread of insects and diseases. Hence, controlling insects and diseases might be one of the important technical issues shaping the cultivation in large scale, although *X. sorbifolia* is resistant, relatively, to diseases and insect pests. Root-knot nematode (*Meloidogyne* spp.), psyllids (*Agonoscena xanthoceratis*) and oriental bud chafer (*Semca orientalis*) are the major pests. The root-knot nematode leads to yellowing of the seedling and of the young tree, and the psyllids induce smudge. Stem rot found on younger plant was caused by *Fusarium* sp. and *Verticillum* sp. [4]. Insecticides and fungicides have been utilized as a common and effective control measure as yet. Physical removal is also used in practice. Besides these, a comprehensive control system which integrates utilization of special and abroad-spectrum pesticides, biological control, biodiversity improvement, and forest tending has not been established.

7. The multifunctionality of *X. sorbifolia*

X. sorbifolia is a multipurpose plant, which plays other important roles in addition to oil production for biodiesel. Its various potential uses are summarized in Fig. 1.

7.1. Whole plant

X. sorbifolia has been applied for carbon sink, soil and water conservation, and land reclamation in mining area [11]. It can be used for landscaping and for its nectar due to its graceful gesture, beautiful leaves, and flourishing appealing flowers with a long flowering season (up to 40 days or more).

7.2. Trunks and branches

The trunks and branches of *X. sorbifolia* are used as traditional Mongolian medicine for the treatment of rheumatoid arthritis, rheumatic heart disease, and adenophyma [12]. The n-butanol extract of the wood exhibited very pronounced anti-inflammatory effects in the models of the early, middle, and late stages of the disease [13]. The main chemicals in these parts of the plant can be categorized into flavonoids, anthraquinones, coumarins, steroids, terpenoids, and benzoquinones. Twenty-eight compounds have been identified. Among these, 3-oxotirucalla-7,24-dien-21-oic acid, oleanolic acid, and Epigallocatechin-($4\beta \rightarrow 8,2\beta \rightarrow$O-7)-epicatechin were found to be active substances repressing human immunodeficiency virus (HIV-1) protease, with their 50% inhibitory concentrations (IC_{50}) being 20, 10, and 70 μg/mL, respectively [14]. Except for the chemical use, the wood can also be exploited for top-grade furniture because of its hard texture and dark maroon color with a beautiful vein pattern [4].

7.3. Leaves

The leaves of *X. sorbifolia* contained about 20% of crude protein consisting of 16 amino acids. By qualitative chemical analysis, ten

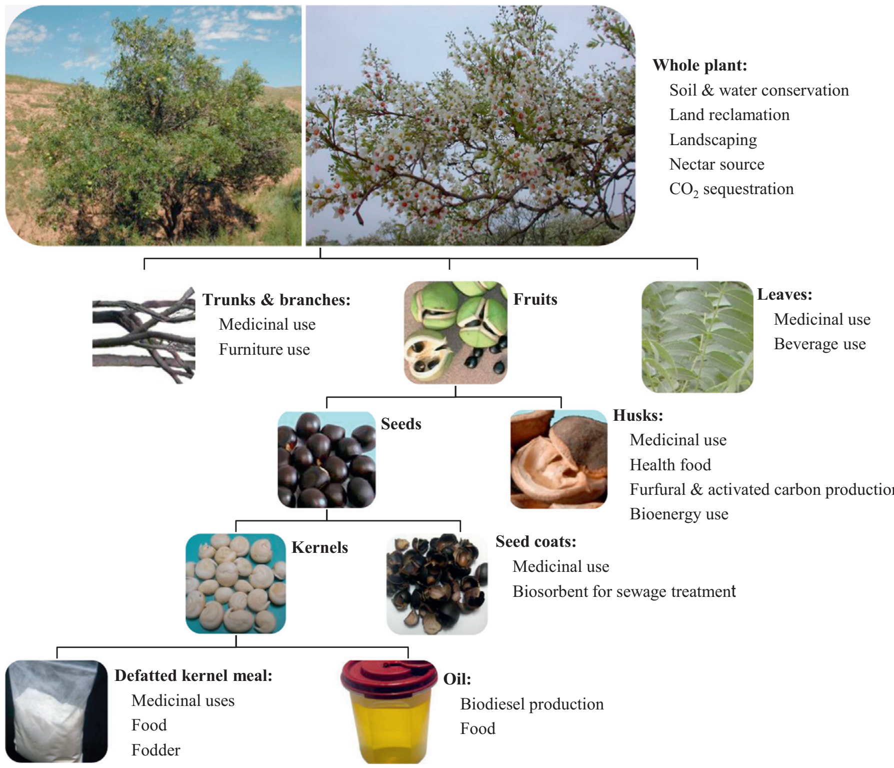

Fig. 1. Uses of *X. sorbifolia.*

types of phytochemicals were found, which are organic acid, alkaloid, reducing sugar, saponin, tannin, flavonoid, anthocyanin, coumarin, phytosterol, and volatile oil [15]. In a further research, three flavonoids and two coumarins were identified as quercetin-3-O-rhamnoside, myricetrin, rutin, fraxetin, and 7-hydroxy-coumarin [16]. An ethanol extract from the leaves relaxed vascular smooth muscle, showing the prospect for preventing and healing cardiovascular problems [17]. Some essential trace elements in human health such as strontium, zinc, barium, boron, copper and manganese were also found in the leaves [15]. Recently, barrigenol type triterpenoids were isolated from the leaves, and some of them showed significant cytotoxic activity [18]. Owing to their nutrition and health-care potential, they are decocted for herbal tea by ordinary people, and concocted leaves have been commercially available.

7.4. Fruits

Young pre-lignified fruits of *X. sorbifolia*, whose folk name is woody melon in Shaanxi, are used as a snack food. The rich and varied phytochemical resources in the ripe fruits laid a solid foundation of their multiple purpose. More than one hundred of secondary compounds have been isolated and identified from carpophore, hull, seed kernel, and seed coat, which included flavonoids, coumarins, steroids, terpenoids, organic acids, and so on.

Extracts from the husk, carpophores and seed-oil-leavings of *X. sorbifolia* have cytotoxicity toward various human cancer cell lines. Major active compounds have been purified and identified as triterpenoid saponins, i.e. 16-O-acetyl-21-O-(4-angeloyl)-α-L-rhamnopyranosyl barringtogenol C, 28-O-β-D-glucopyranosyl 16-deoxybarringtogenol C, barringtogenol C, 16-deoxybarringtogenol C, 21,22-di-O-angeloyl barringtogenol C, 21-O-(3,4-di-O-angeloyl)-β-D-fucopyranosyl barringtogenol C, 22-O-acetyl-21-O-(4′-O-angeloyl)-β-D-fucopyranosyl theasapogenol B, xanifolia O54, xanthohuskisides (A and B), bunkankasaponins (A–D, F) and xanifolia-Ys (Y_0, Y_2, Y_3, Y_7, Y_8, and Y_{10}) [19–25].

7.4.1. Husks

Crude extracts from the husks could significantly ameliorate the learning and memory dysfunction in animal models, and the xanthoceraside was found to be the major active compound. The mechanism may be related to inhibiting oxidative stress and inflammatory responses, improving cholinergic functions, increasing acetylcholinesterase levels in the nervous system, releasing glutamate, and resisting the brain hypoxia. Thus, the multifactorial effects of this chemical make it a promising candidate for producing medicines or health foods to prevent or cure cerebral dysfunction related diseases such as Alzheimer's disease, Parkinson's disease, enuresis, urinary incontinence, dementia, and for improving memory and cerebral functions [26–30]. According to a patent invented by researchers from the Fuzhou University [31], the husks contained cellulose (38.20 g/100 g), hemicellulose (22.11 g/100 g), lignin (17.11 g/100 g), pectin (2.30 g/100 g), wax (5.15 g/100 g), water extractives (9.36 g/100 g), and ash (5.77 g/100 g). This invention provided a method for comprehensively utilizing the shells. After the pretreatment with steam explosion, a slurry material was obtained and treated with microbial transformation. The hemicellulose and partial cellulose were transformed into biological natural gas through acidification and methanation. Then, the enzymatically hydrolyzed lignin was isolated from the residues. The cellulose in the residues was moved into cellulosic ethanol production process. After ethanol recovery, the leavings were used as fertilizer or boiler fuel. Apart from these, the husks have also been considered to be used as a substrate for productions of furfural and activated carbon [4,32,33].

7.4.2. Seed coats

Cleomiscosin B has been isolated from a methanolic extract from the seed coats of *X. sorbifolia*, which showed in vitro inhibitory activity against human immunodeficiency virus type 1 (HIV-1) with CC_{50} value to exceed 200 μg/mL, EC_{50} value of 8.61–12.76 μg/mL, and selective index of 15.67–23.23. According to our

Table 1
Fatty acid profile of *X. sorbifolia* oil compared with other vegetable oils.

Fatty acid (n:m)[a]	*X. sorbifolia*[b]	Palm[c]	Sunflower[c]	Soybean[c]	Jatropha[d]	Cottonseed[e]
Lauric (12:0)	–	0.1	–	–	–	–
Myristic (14:0)	–	0.7	–	–	–	1.2
Palmitic (16:0)	5.2	36.7	6.2	11.3	14.1	29.0
Palmitoleic (16:1)	–	0.1	0.1	0.1	0.5	0.8
Margaric (17:0)	–	–	–	–	–	0.2
Stearic (18:0)	2.2	6.6	3.7	3.6	6.8	5.9
Oleic (18:1)	28.6	46.1	25.2	24.9	38.6	9.8
Linoleic (18:2)	43.3	8.6	63.1	53.0	36.0	50.2
Linolenic (18:3)	0.5	0.3	0.2	6.1	0.2	–
Arachidic (20:0)	0.4	0.4	0.3	0.3	0.2	0.8
Gadoleic (20:1)	6.8	0.2	0.2	0.3	–	0.4
Heneicosanoic (21:0)	0.4	–	–	–	–	–
Behenic (22:0)	0.6	0.1	0.7	–	–	0.5
Erucic (22:1)	8.7	–	0.1	0.3	–	1.1
Tricosanoic (23:0)	–	–	–	–	–	0.1
Lignoceric (24:0)	0.3	0.1	0.2	0.1	3.6	0.2
Nervonic (24:1)	3.0	–	–	–	–	0.1

[a] n:m=no. of carbon atoms: unsaturated centers.
[b] [37].
[c] [50].
[d] [42].
[e] [51].

Table 2
Physicochemical properties of *X. sorbifolia* seed oil.

Property	**Unit**	**Value**	**References**
Density at 20 °C	kg/L	0.914	[52]
Kinematic viscosity at 40 °C	mm^2/s	38.11	[52]
Caloric value	MJ/kg	39.7	[52]
Peroxide value	meq O_2/kg	0.16	[52]
Acid value	mg KOH/g	0.601	[52]
Free fatty acid	%	0.3	[37]
Iodine value	g I2/100 g	113	[37]
Saponification value	mg KOH/g	176	[37]

previous work, the seed coats are a promising bio-sorbent for removal of cationic dyes from aqueous solutions [34].

7.4.3. Defatted seed kernel meal

The seeds of *X. sorbifolia* were found to be a nutritionally valuable herbal protein source. The defatted seed kernel meal is rich in proteins (60.5 g/100 g) with an excellent amino acid profile, in which seventeen amino acids were isolated with a high percentage of seven essential amino acids accounted for 39% by weight of the total amino acids. The essential amino acid index was 75, higher than that of peanut proteins whose counterpart was 64. The protein efficiency ratio of the kernel was 2.85, larger than those of concentrated proteins from soybean and sunflower seeds. The proteins from the kernel also showed good properties of emulsification and foaming, revealing a potential use in food industry [35,36]. Feeding experiments on pigs established the substitute of the kernel meal for the soy meal, and the former was favorable to the weight development during the growing-finishing period [4]. The seed kernel of *X. sorbifolia* is a folk medicine employed for treating enuresis in China, and a series product has been developed by some pharmaceutical manufacturers in recent years.

7.4.4. Seed kernel oil

The oil obtained from the seed kernel of *X. sorbifolia* was semi-drying one. As shown in Table 1, it contained unsaturated fatty acids up to 90.9% of the total fatty acids, which have potential health benefits [37]. The oil also contains other potentially cardio-protective constituents, including phytosterols and tocopherols. These data indicate that the oil can serve as raw materials for soap and health-care food production [38–40]. The fatty acid profile of the *X. sorbifolia* seed oil resembles those reported for some conventional oils used as biodiesel production feedstocks (palm, sunflower, soybean, jatropha and cottonseed). Their dominant fatty acids are C16 and C18, with the oleic and linoleic acids more than half (Table 1). The chemical composition signifies its probable use as a biodiesel production feedstock. The physicochemical properties of parent oil or fat usually determine the production process and the performance of the synthesized biodiesel. The physicochemical properties of *X. sorbifolia* oil are listed in Table 2. Density, kinematic viscosity, and caloric value of crude *X. sorbifolia* seed oil were 0.914 kg/L, 38.11 mm^2/s, and 39.7 MJ/kg, respectively, which are within the ranges of the counterparts of some vegetable oils as biodiesel feedstocks [41]. Peroxide value of the oil showed a low value of 0.16 meq O_2/kg, proving the oxidative stability relatively. The alkali- and acid-catalyzed transesterifications of vegetable oils have been highly cost-efficient and simple methods for the biodiesel production, and are widely practiced nowadays. The alkali-catalyzed process has been a preferred option which can obtain high purity and high yield of biodiesel in a short time (30–60 min) [42]. However, it is very sensitive to the purity of the reactants. The free fatty acids (FFA) can react with the alkali catalysts and form soap, leading to difficulty in separating products and a lower yield of biodiesel. Accordingly, high FFA content is unfavorable in this process, and an upper limit of 1% FFA for the base-catalyzed transesterification has been given by some literatures [42,43]. Recently, some articles have provided information on the biodiesel production using the seed oil of *X. sorbifolia* [37,44–48]. The oil contains about 0.3% FFA, which is inferior to the limit. The iodine value of the oil was 113 g I_2/100 g, meeting the biodiesel quality specifications (< 120 g I_2/100 g) [49]. The yield of methyl esters from the refined oil of *X. sorbifolia* was 89% by a conventional alkali-catalyzed method under the optimal condition in 60 min [46]. Microwave technology and unconventional catalysts were employed to strengthen transesterification of the oil to the biodiesel. Under microwave irradiation, the yield of methyl esters reached 96% when the reactions were catalyzed by KOH, high alkaline anion exchange resins or heteropolyacid $Cs_{2.5}H_{0.5}PW_{12}O_{40}$ [44,45,47]. Some of the important quality parameters of the biodiesel derived from the oil, along with the standard specifications of China, are shown in Table 3.

Except for the distillation value found to be slightly exceeded, other measured values were in line with the China standard GB/T 20828. Thus, the oil is an acceptable feedstock for biodiesel production [37].

7.5. Cascade utilization of the biomass

The average proportions starting with 100 g of the dry fruits/capsules of *X. sorbifolia* are shown in Fig. 2. Though the kernels have high lipid content (67%), the oil represents only 16% of the fruits and about 34% on a seed basis [53]. As shown in Fig. 2, the quantity of the by-product, including the fruit husks, the seed shells and the defatted kernel meal, is over five times more than that of the seed oil. Under planting in large scale, the considerable amounts of branches and leaves will be brought out in pruning and in felling for re-juvenescence. If these co-products are not effectively used and discarded as wastes, they would become burdensome on environment and companies or farmers that deal with them. However, the economic benefit from comprehensive utilization of such byproducts is ten times more than that from the oil, according to the evaluation done by Xu et al. [4]. The leaves have been used as an ingredient of composite black tea with a market price of about 4000 Yuan/kg. The wood from the tree is a traditional ethnic-minority drug with narrow applications, whose market price is about 1 Yuan/kg. The medicines made from the seed kernel meal have been presented at market. However, there is little information on their productions and sales. The medicinal uses of the leaf, husk and seed coat are only suppositions based on their phytochemical constitute, or are still in pre-clinical trials. Most seeds are used for afforestation nowadays. The edible oil and the biodiesel have not been commercially available in bulk as yet, because of the shortage of the raw material. Other utilizations of the biomass are still at laboratory stage. In view of the huge resource potential in the future, bulk utilization of the biomass residues should be set up. Bio-energy is a promising candidate. However, aside from the patent on production of ethanol and biological natural gas from the husks, hardly any information on energy utilization of the biomass can be obtained now [31].

Table 3
Properties of biodiesel from *X. sorbifolia* compared to GB/T 20828 standard [37].

Specification	Unit	*X. sorbifolia*	GB/T 20828
Density at 20 °C	g/cm^3	0.872	0.820–0.900
Viscosity 40 °C	mm^2/s	4.181	1.9–6.0
Distillation	% at °C	362	90%, 360 °C
Flash point	°C	165[a]	130 min
Sulfur	wt%	0.0016	0.05% for S 50 Grade 0.005% for S 500 Grade
Carbon residue (10% dist. residue)	wt%	0.23	0.3 max
Sulfated ash	wt%	0.014	0.02 max
Water	mg/kg	0.0531%	500 max
Mechanical admixtures		None	None
Copper strip corrosion	3 h/50 °C	1[a]	1 max
Cetane number		58.0	49 min
Acid value	mg KOH/g	0.36	0.80 max
Free glycerol	wt%	Not detected	0.020 max
Total glycerol	wt%	0.11	0.240 max
Cold filter plugging point		−3	Report

[a] Reported by Li et al. [47].

8. Cultivation history and current status of *X. sorbifolia* in China

X. sorbifolia has a long planting history in China. In ancient times, it was sporadically planted around temples to provide smokeless illuminating oil and edible oil for monks. However, its commercial cultivation history is short, being launched in the 1950s. There are two violent rises and one fall in its cultivation history. In the 1960s and the 1970s, it was planted on a large scale in the northern China to make up for the shortage of edible oils in the country during those years. By the end of the 1970s, the plantation area reached about 47,000 ha. However, in the next two decades, deforestation was widespread and only about 6.7 thousand hectares of the plantation survived. The resources, including superior individuals, seed and cutting orchards and collection nurseries, were destroyed with almost no retention [4]. The survived trees are in a wild or semi-wild state. According to the investigation done by Mou et al. in 2005 [5], the horizontal distribution of the plant is discrete, showing a patchy pattern when viewed as a whole. Its resource was most abundant in the Inner Mongolia autonomous region and the provinces of Hebei, Henan, Shanxi, Shaanxi, and Gansu. The largest pure plantation was found in Inner Mongolia, with an area over 1800 ha. A small number of acres of pure plantation, with a total about 13 ha, were also found in Henan province. In Beijing, Anhui, Ningxia, and Xinjiang, the tree was planted individually or in small plot size, and it is mainly present in secondary forests in the other provinces. In 2007, *X. sorbifolia* was recommended as a woody energy plant, and the plantation ushered in the other violent rise. The planting target of 1.33×10^5 ha in the Eleventh Five-years has been hit. Follow-up plans have been developed or are developing by governments at various levels, and the total area may be over 5×10^5 ha by 2020, mainly in Inner Mongolia, Liaoning, Jilin, Hebei, Shanxi, Shaanxi, Xinjiang, Gansu, and Shandong. However, the practical contradiction between the rapid expansion of the cultivation scale and the shortage of superior propagating materials leads to the fact that the seedlings from the ordinary trees without any selective preference have been widely used in plantations in recent years, embedding a big potential trouble in the industry of *X. sorbifolia*. The forests planted in the 20th century are almost owned by the state or collectives, and operated by state-owned forest farms or administrative villages. Some new types of organization for agricultural activities have been established for the biofuel industry of the tree. The typical and universal one is the form of company + farmer + government + production base. The system is operated as illustrated in Fig. 3. The base is the center of the system, and is operated by a means of made-to-order farming mode. The companies sign plantation and trade contracts with the local farmers, providing seedlings, fertilizers, pesticides, and technical services to the farmers, and purchasing farm products from the farmers. Correspondingly, the farmers provide a labor force, undertake day-to-day management of the plantation, and sell farm products to the companies. The government sectors are policy makers and propagandists and give financial and taxation supports to the farmers and the companies. This organization form is a large-scale cultivation style. According to the Ministry of Finance on the issuance of “Bio-energy and io-chemical Non-food Incentive Funds Interim Measures for the

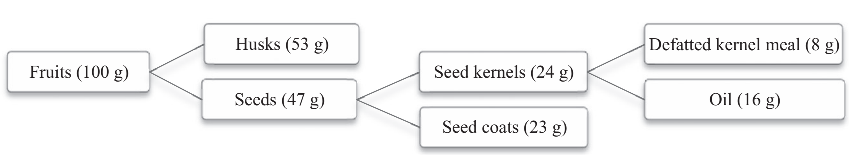

Fig. 2. Average fractions of the fruit of *X. sorbifolia*.

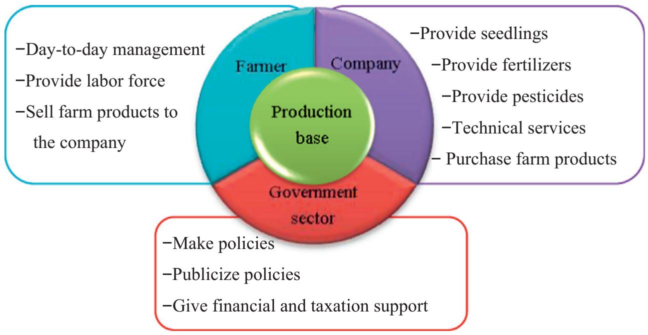

Fig. 3. A typical organizational structure of agricultural activities in the biofuel industry of *X. sorbifolia.*

Administration Guide", one of the eligibility criteria for financial incentive funds for forest biodiesel industry development is the prerequisite that the company has an annual biodiesel output over 3×10^4 t, with at least 2×10^4 ha of unused land and 33 ha of seedling breeding base for the raw material production in the expansion of industrialization demonstration.

9. Productivity and economic benefit of ;*X. sorbifolia* plantation

Productivity of *X. sorbifolia* plantation is controversial. Some people believe that the tree produces a high yield of seeds, but others do not think so. The former base their viewpoint on individual yield and focus on the potential productivity, while the latter ground their own opinion on yield per area and concentrate on the realistic productivity. The tree has a short juvenile period and a long lifespan. It starts yielding from the third to fourth, exceptionally second, year of planting if the plantation is well-managed, and it steps into a full bearing period after about 20 years. The seed yield per tree is high to some individuals. The yields of 23.8, 35, and 59.5 kg/tree have been obtained from 40-, 80-, and 100-year-old trees, respectively. It keeps producing seeds for many years. The upper age limit for seed production is not yet clear, but more than 10 kg of seeds had been harvested on a 270-year-old tree [4]. However, in practice, the seed yield per unit area is low and shows wide variations, because the trees are heterogenous and undomesticated. The male flowers accounted for over 90% of the total flowers, and even some trees are nearly all male flowers and hardly bear fruit on whole trees [54]. Ninety percent of hermaphrodite flowers can be fertilized after natural pollination, while only 2% of the fruits achieve their final maturity [55]. The low fruition rate has been notoriously referred to as "thousands of flowers but one fruit" [56]. The seed yield is unstable, changing with individuals, ages, and years. An eight-year yield monitor experiment was conducted in 1966–1968 and 1974–1978 on an *X. sorbifolia* plantation of 0.28 ha with 270 trees in the campus of the Inner Mongolia Forestry College. The plantation was established in 1964 by using seedlings from undistinguished seeds. In the population investigated, about 15% were always high yield with output near upon half of the total; about 10% of them bore more fruits in their early years, while only few after being planted 10 years later; another 15% were low yield in their early years but high yield after being planted 10 years later; nearly one third were second-raters, which bore with average yield every year or were in "on-year" much less than in "off-year"; another one third were always low yield, bearing few fruits or none. The fact that the bad mixed with the good put a mask of low yield per area on existing plantations. This species has a very short cultivation history and is found growing in a semi-wild state. So far, there are no plantations with appropriate area in the full bearing period suitable for yield measurement. The yield per area reported by some literatures was the result estimated by multiplying the yield per tree by planting density designed [4]. According to an investigation in eight provinces conducted by Hou et al. [57], the existing plantations showed low seed yield, ranging from 122 kg/ha to 2543 kg/ha. It is largely due to the lack of improved variety and the extensive management. Their study also demonstrated that the tree has a high potential in productivity and economic benefit under intensive operation and using elite germplasm. The yields of the seed and the oil would be 3 t/ha and 1 t/ha, respectively, for a 20-year-old plantation, and 6 t/ha and 2 t/ha, respectively, for a 20-year-old plantation [4,57].

The cost for establishing 1 ha of plantation was about 3000 Yuan (1 Yuan≈0.16 US$; Feb. 2013), including 750 Yuan for land rent for a period of 30 years, 450 Yuan for seedling, and 1800 Yuan for site preparation and planting. Coincidentally, farmers will get a subsidy of 3000 Yuan/ha to forest for biofuel manufacture. The costs can be offsetted by the subsidy.

At the seed production stage, the annual costs were extrapolated depending upon the seed yield according to Ref. [58].

(1) Fertilizer cost: 117 Yuan/t seed;
(2) labor cost: 300 Yuan/t seed;
(3) transportation cost (feedstock transportation from the field to the collection site): 24.5 Yuan/t seed.

As a result, the total input cost at this stage was 441.5 Yuan/t seed. The present market price of *X. sorbifolia* seed is 90 Yuan/kg, which is a ridiculously high price jacked by the short supply for the rapid expansion of the plantations. It is clearly inappropriate to use this price to calculate the income from the sale of the seeds in the future. A reasonable price was reckoned as 1.5 Yuan/kg [57]. So, the net profit of the seed was 1500−441.5 = 1058.5 Yuan/t. The potential profits per hectare were 3175.5 Yuan and 6351 Yuan for 10-year-old plantation and 20-year-old plantation, respectively. They are higher than that of 1050–1085 Yuan/ha for rape in Gansu, while lower than that of 8398 Yuan/ha for wheat or corn in Henan. Thus, from an economic point of view, planting the tree on low-yielding fields, such as in Gansu, is feasible [57].

At the biodiesel production stage, the costs were calculated as the following [58,59].

(1) Seed oil extraction cost: 120 Yuan/t biodiesel;
(2) transesterification cost: 299 Yuan/t biodiesel;
(3) labor cost: 36 Yuan/t biodiesel;
(4) water cost: 20 Yuan/t biodiesel;
(5) transportation cost (feedstock transportation from the collection site to the biodiesel refinery and biodiesel transportation from the biodiesel factory to the distribution center): 182 Yuan/t biodiesel;
(6) depreciation and repair of fixed assets: 374 Yuan/t biodiesel;
(7) seed cost: 5407 Yuan/t biodiesel (supposing seed price, oil content, extraction rate and biodiesel yield are 1500 Yuan/t, 34%, 85% and 96%, respectively).

Consequently, the total manufacturing cost at this stage was 6438 Yuan/t biodiesel. The main component is the seed cost, accounting for 84%. To produce 1 t of biodiesel, crude glycerin of 0.11 t was produced as a by-product, being worth 220 Yuan according to the present market price. After compensation by the glycerin, the net cost of the biodiesel was reduced to 6218 Yuan/t. The benchmark price of fossil diesel was 8010 Yuan/t in March 2013. The estimated cost is competitive with the fossil diesel. The producing costs were 7676 and 6676 Yuan/t for the biodiesels from jatropha oil and palm oil, respectively [59]. Therefore, the *X. sorbifolia* oil is also competitive with these oils in the biodiesel industry in China. However, the

feasibility at this stage is based on the low seed price of 1500 Yuan/t, which is further grounded on the higher seed yield per hectare derived from the assumption of using elite line and intensive operation.

10. Advantages and disadvantages for biodiesel production from *X. sorbifolia*

X. sorbifolia has some potential benefits as a bio-energy feedstock plant, as summarized below.

- Growing well in marginal land, and thereof not competing with food production for land use. It is multi-resistant and adaptable to plant widely on marginal lands in northern China, where the great prospect of supplying bio-energy resources and the co-benefits of improving eco-environment and accelerating rural development are considerable for the abundant marginal land [60].
- Short in a juvenile period, and long in a lifespan and a productive period. It is easy to cultivate from seed and grows relatively quickly. It can start giving yields right from the 3–4th year and has a productive life over 100 years.
- Considerable variations in the population. The trees show considerable differences in morphological characters of the fruits and the flowers, contents of the oil and other chemical constituents, seed productivities, and other aspects. This huge variation is very important to breeders for selection and breeding programs.
- High oil content in the seed kernel.
- Multipurpose plant with potential for full use.
- Policy supports. It has been designated a key species introducing it into "Forest-Oil Integration" project and given special support by government sectors.

Despite the technical suitability and the beneficial factors of biodiesel production from *X. sorbifolia*, there are still a lot of disadvantages to be faced by China. The adverse factors are listed as following:

- Low seed yield per unit area, especially under poor site conditions and extensive management. The little knowledge about its potential yield under sub-optimal and marginal conditions makes it difficult predicting the yields from plantations on the marginal land, where the tree is going to be or being afforested in large scale.
- Sensitive seed yields to soil fertility and moisture availability. The tree needs one or two irrigation and fertilization annually for better harvesting. However, most cultivating area is very scarce in water resources.
- Unstable seed yield.
- Lack in superior varieties and rapid propagation techniques. There are no identified varieties yet that are reliably high yielding.
- Large amount of byproducts accompanied with the oil production.
- Immaturation in the technologies of comprehensive utilization and lack in mature products.
- Edible nature of the oil. Its oil is edible with health-care potential, and therefore, the oil may be robed from biodiesel production by food industry, increasing complexity and uncertainty in the future.
- Misleading of improper information. Some information available is not based upon actual research results, misleading governments, enterprises, farmers, and even some scholars.

11. Some suggestions

Will the current boom in cultivation of *X. sorbifolia* end with a bust as in the last century? To answer this question, the reason for deforestation in that era should be outlined. Besides political mood for the Chinese Cultural Revolution, two culprits were responsible for it. One is the low productivity and thereof low economic efficiency. The other is the disappearance of the use as edible oil because the traditional herbal oils had met the demand for food since the Reform and Opening-up of China. On the basis of findings by some researchers, the higher seed yield was only a potential! Today, the problem of the low yield still exists although the political barrier has been removed, and the new purpose for biodiesel production established. The current resurgence of planting *X. sorbifolia* would collapse into the old trap again if the problem was not well solved. Consequently, a long way needs to go before a commercial process in large-scale can be really achieved. However, the opportunities are also existing simultaneously, as mentioned above. Here, we present some suggestions for research and development in sustainable biodiesel production from *X. sorbifolia* to avoid the risk. Firstly, genetic and breeding researches should be intensively done to clarify the reasons for the low fruit-setting rate and to produce improved varieties with high-yield potential on marginal lands. Secondly, clonal propagation technologies should be developed to facilitate the popularization of the improved varieties. These two aspects are essential prerequisites for the economic exploitation of *X. sorbifolia,* and need to be solved urgently. Thirdly, the remaining plantations and seed stands need to be renovated and rejuvenated to improve their productivities and to supply materials for the biodiesel production and the research in genetics, breeding, cultivation, comprehensive utilization and other fields. Fourthly, high-yield cultivation techniques based on the marginal land conditions should be instituted and various agronomic important factors such as planting density, nutrient and water demand and pruning time should be investigated. Finally, the researches on comprehensive utilization are suggested to be strengthened to contribute towards the cost reduction of the biodiesel by compensation with integral valorization of the co-products. The bulk utilization, such as energy utilization, of the biomass residues should be well developed.

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